DIGITALLY POSITIONED MICROMIRROR FOR OPEN-LOOP CONTROLLED APPLICATIONS

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ABSTRACT

The power consumption and complexity of the close-loop control electronics are the major barriers that limit the applications of optical switches, beam steering devices and other micromirrors. To eliminate or lower the barriers, it is desirable to have a micromirror with precise, digitally positioned angles. This paper reports the first investigation to design a digitally positioned micromirror and characterize its precision levels. From the experimental results, very encouraging results have been reported for the first designed digital micromirror: +/-0.01^o position precision has been achieved with the mirrors fabricated in the same batch but operated sporadically over a 3-month period. In order to reduce the number of the electrical drives for the mirror and increase the maximum tilting angle, an improved device was designed and tested. 0.02^o/V precision has been demonstrated in the digital levels via experimental testing and +/-0.03^o position precision of repeatability has been achieved within the angle range +/-3.5^o. The electrical-mechanical performance of the mirror is discussed here. Standard deviation of average angle and angle variance per driving voltage within the digital levels are identified to characterize the digital behavior of the mirror.

INTRODUCTION

A large percentage of optical applications require high precision position control. Precision position control among different optical elements is critical to the manufacturing and operation of different optoelectronic modules for optical communication, optical interconnects, free space optical switching and other systems [1,2]. Micro-Electro-Mechanical Systems (MEMS), which are integrated micro devices and systems combining electrical and mechanical components, provide a novel and cost effective solution to these applications [1-4]. However, close-loop control is demanded for most MEMS devices in order to achieve the desired precision. The power consumption and complexity of the close-loop control electronics are the major barriers that limit the applications of optical switches, beam steering devices, and other micromirrors. To eliminate or lower these barriers, it is always desirable to have a micromirror with precise, digitally positioned angles. The device can be used for open-loop controlled applications or can be used to reduce the control range and the associated power consumption and complex electronics. Compared to analog micromirror devices fabricated through MEMS technology [3,4], the digital micromirror is more repeatable and suited to large-scale integration. Due to the reduction of the range and power consumption of control electronics, the digital mirror-based MEMS approach seems to be best poised to fill the near-term need for large optical crossconnect. This paper consists of the novel concepts and designs of digitally positioned micromirrors, as well as the investigation of their precision levels.

FABRICATION AND PRINCIPLE

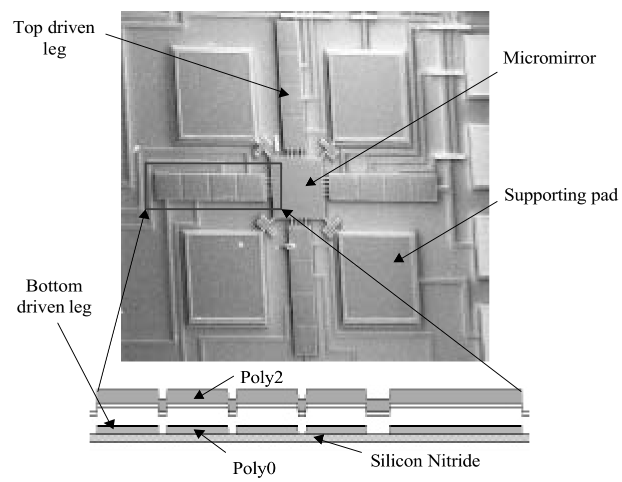

Figure 1: SEM of a digital micromirror

The digital micromirrors studied in this paper were fabricated through the production run of the multi-user MEMS processes (MUMPs) from Cronos Integrated Microsystems. MUMPs offer three patternable layers of polysilicon, and two sacrificial layers of phosphosilicate glass on a base layer of silicon nitride. After fabrication, MEMS devices are ‘released’ by removing the sacrificial glass layers in buffered hydrofluoric acid (HF). Figure 1 depicts the micromirror’s structure studied in this paper after release. The mirror is connected to the supporting pads by four flexures. There are four top “driven legs” along the four sides of the micromirror in order to tilt it in 2 directions. The top electrode is constructed by Poly2 layer with Poly0 for the bottom electrode. Under each top driven leg, four bottom electrodes define the tilting angle affected by this leg.

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The operation principle of the digital positioning is illustrated in Figure 2. When a voltage is applied on the first bottom electrode under one top driven leg, the electrostatic force drives the top leg toward to the substrate and tilts the mirror surface through the connection between the top leg and the mirror surface. Because of the electrostatic "snap down" effect, the top driven leg collapses against the substrate when the applied voltage exceeds a threshold value. After the "snap down" of the first electrode, the tilting angle of the mirror will not change with respect to the increase in the applied voltage unless a voltage is applied on other bottom electrodes because the increased electrostatic force is balanced by the contact force of the substrate and will not affect the tilting angle of the mirror. Therefore, the first digital angle is obtained. Through different geometric configurations controlled by the sequence of the "snap down", the mirror can reach different digital angles.

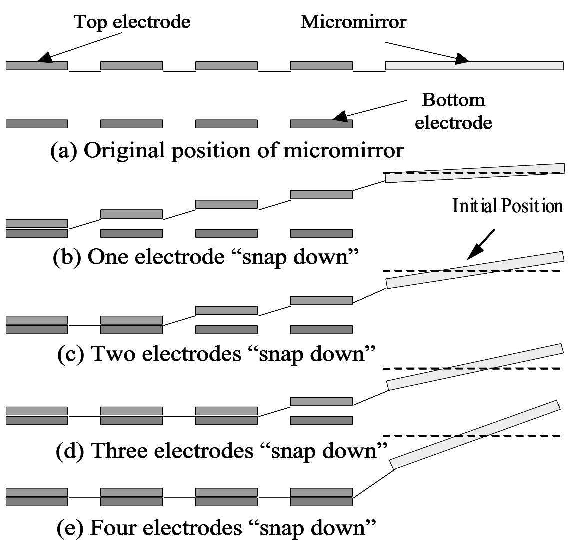


Figure 2: Operation principle of the digital positioning

REPEATABILITY

To determine the tilting angles and their digital performance, an interferometric microscope "ZYGO" is used. The experimental setup is illustrated in Figure 3. A resistor is used to avoid circuit short after the snap down. Figure 4 shows the surface profiles of the measurement results of two tilting angles corresponding to one electrode and four electrodes "snap down". The digital performance can be easily illustrated through these pictures. Figure 5 presents the repeatability of a device to reach a particular angle corresponding to two electrodes "snap down". The angular positioning is good to +/-0.01^{o} with three consecutive measurements. With different devices characterized, the repeatability is also good down to +/-0.01^{o} (see Figure 6 and Table 2). More importantly, the measurements for Figures 5 were conducted three months after those for Figure 6. Clearly indicated, aging (without package protection) did not affect the digital performance.

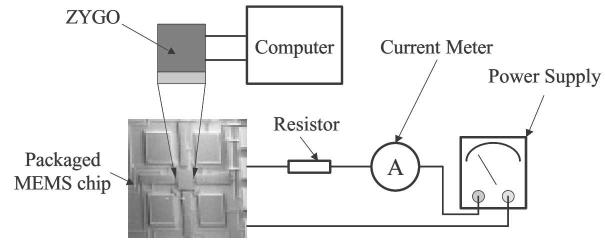
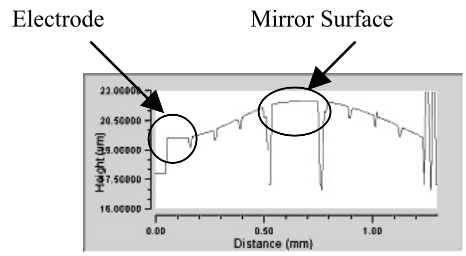
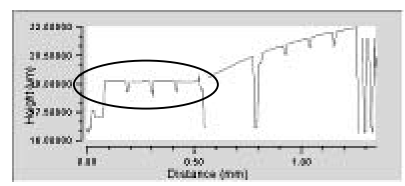


Figure 3: Experimental setup of the measurement of the tilting angle

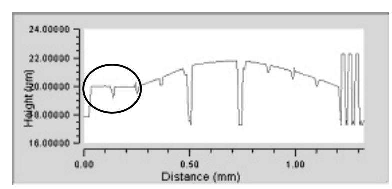


(a) One side, one electrode "snap down"
(Tilting angle: 0.106º)

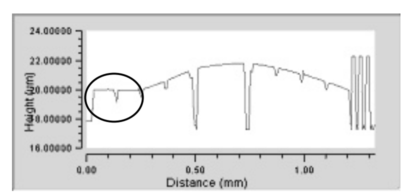


(b) One side, four electrodes "snap down"
(Tilting angle: 0.382º)

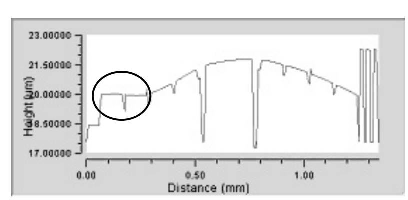
Figure 4: Digital performance measured by interferometric microscope



(a) First measurement
(Tilting angle: 0.148º)

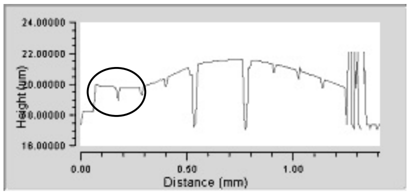


(b) Second measurement
(Tilting angle: 0.150º)

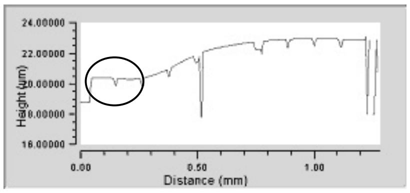


(c) Third measurement
(Tilt angle: 0.142º)

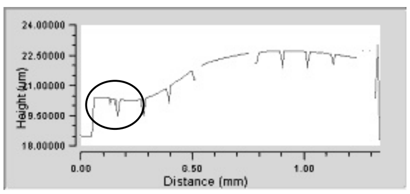
Figure 5: Repeatability analysis for the same device



(a) First device
(Tilting angle: 0.148º)



(b) Second device
(Tilting angle: 0.145º)



(c) Third device
(Tilt angle: 0.147º)

Figure 6: Repeatability analysis for the different devices

Tables 1 and 2 summarize the measured results of the digital angles. Four digitally positioned angles are obtained within a +/-0.01^o precision for one device with three measurements and a +/-0.01^o precision for three different devices fabricated in the same batch.

Table 1: Repeatability analysis for the same device

Tilting angle (º)	One electrode "snap down"	Two electrodes "snap down"	Three electrodes "snap down"	Four electrodes "snap down"
First measurement	0.106	0.148	0.279	0.382
Second measurement	0.109	0.142	0.285	0.379
Third measurement	0.101	0.150	0.284	0.380
Standard deviation	0.004	0.004	0.003	0.002
Angle precision	+/-0.01			

Table 2: Repeatability analysis for different devices

Tilting angle (º)	One electrode "snap down"	Two electrodes "snap down"	Three electrodes "snap down"	Four electrodes "snap down"
First device	0.106	0.148	0.279	0.382
Second device	0.101	0.145	0.279	0.392
Third device	0.103	0.147	0.274	0.395
Standard deviation	0.003	0.002	0.003	0.007
Angle precision	+/-0.01			

IMPROVED DESIGN

The maximum tilting angle from the micromirror in Figure 1 is about 0.4^o, which is not large enough for most optical applications. To obtain a larger tilting angle, pre-stressed beams are used to increase the gap between the top and bottom electrodes, and then increase the range of the micromirror's tilting angle. Figure 7 shows the improved design. After release and packaging, the gap between top and bottom electrodes is increased to 13.2 microns from the initial gap of 2.75 microns for the mirror in Figure 7. Therefore, the range of tilting angles during the experiment was increased to +/-3.5^o. The gap can be controlled by changing the design of the pre-stressed beams [5].

For the micromirror in Figure 1, 4 bottom electrodes are required to obtain 4 digital angles in each top driven leg direction, resulting in a total of 16 bottom electrodes for one micromirror. The large number of bottom electrodes is not practical for applications that need large-scale integration of the digital micromirror arrays such as free space optic crossconnect. In order to reduce the number of bottom electrodes and keep the digital performance at the same time, the shape of top driven legs for the improved design is changed. Each top driven leg consists of four segmented plates, connected with each other through beam connectors. Through the sequence of the "snap down" of the different plates controlled by the range of the applied voltage, the mirror can reach different digital angles.

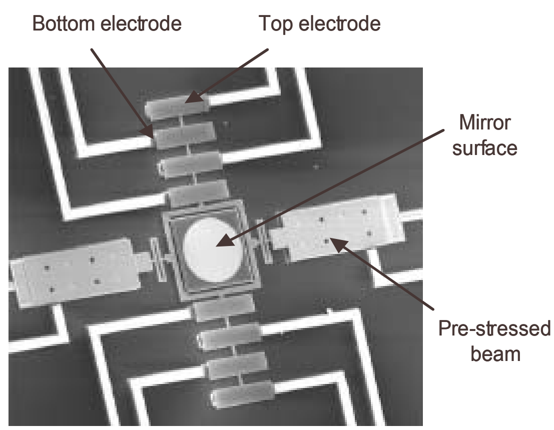


Figure 7: SEM of an improved digital micromirror

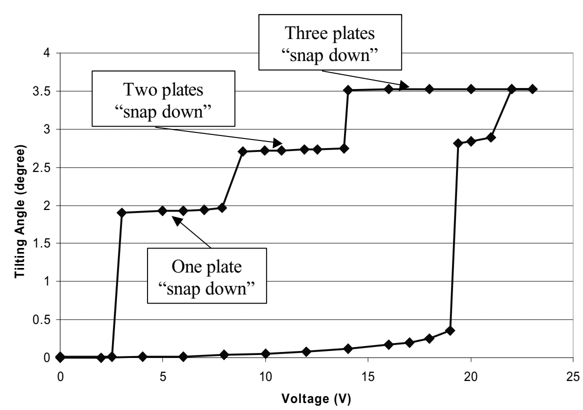


Figure 8: Experimental result of the digital performance of the micromirror in Figure 7

Figure 8 depicts the experimental result of the digital performance of the micromirror in Figure 7. The behavior of the micromirror shows a hysteresis effect for increasing and decreasing voltages. The origin of the hysteresis comes from a difference in the electrostatic field distribution between the micromirror before and after pull-in. Once the micromirror is collapsed, the electrostatic forces strongly increase as a result of the decreased gap spacing and a large decrease in the driving voltage is needed before bending and rotating forces overcome the electrostatic forces again.

Although as many digital levels cannot be obtained as the driving voltage is increased, three digital levels corresponding to the number of the plates snap down's can be reached when decreasing the driving voltage. In order to characterize the digital performance, the standard deviation of average angle σ for different measurements and different devices is calculated as:

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N}(A-\overline{A})^2}{N-1}}$$

where A is the average angle of the mirror or measurement, $\overline{A}$ is the average angle of the total mirrors or measurements, N is the number of mirrors or measurements.

Table 3 shows σ for the three different measurements of the same mirror and three different mirrors under the same batch for one plate "snap down". A +/-0.02^o precision for one device with three measurements and a +/-0.03^o precision for three different devices fabricated under the same batch have been obtained.

Table 3: σ for one plate "snap down"

Average tilting angle (^{o})	Different measurements	Different devices
First	1.93585	1.92368
Second	1.93349	1.881645
Third	1.9017	1.87447
σ	0.019	0.027
Angle precision	+/-0.02	+/-0.03

Table 4: K for the micromirror in Figure 8

	One plate "snap down"	Two plates "snap down"	Three plates "snap down"
Maximum tilting angle change (^{o})	0.059	0.05	0.010
Voltage range (V)	3 to 7.89	8.89 to 13.84	14 to 23
K (^{o}/V)	0.012	0.01	0.002

Another factor to characterize the digital performance is "the tilting angle variance per driving voltage in the digital level", expressed as:

$$K = \frac{\text{Tilting angle change of the digital level}}{\text{Voltage range of the digital level}}$$

As illustrated in the definition, K should be smaller in order to get the better digital performance. Table 4 shows the K for the different digital levels in Figure 8. A 0.012^o/V precision has been obtained in the digital levels.

Although the digital performance is highly affected by the fabrication and packaging process, it can be improved by proper design. These design parameters include the gap between the top and bottom electrodes, flexure geometry, plate geometry, beam connector geometry and bottom electrode geometry. By changing these parameters, the digital performance can be improved with respect to different applications.

With the use of increased number of plates along with each electrode, the number of digital angles can be increased substantially. In addition to the digital performance, the mirror has two other important features: 1) the mirror driven by multi-electrode "snap down" is very powerful; it can be used to carry another micromirror for close-loop fine tuning; 2) the driving voltage can be reduced by increasing the size of the top electrodes without affecting the maximum tilting angle of the micromirror.

CONCLUSION

Two different digitally positioned micromirror are reported in this paper. +/-0.01^o angle precision has been achieved with the mirrors fabricated under the same batch for the first mirror. The second mirror shows a 0.012^o/V precision in the digital levels and a +/-0.03^o position precision of repeatability within the angle range +/-3.5^o. Future work includes simulation of the digital performance of the micromirror and improvement of its design for better digital performance.

ACKNOWLEDGMENTS

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